Lecture CFD-3

CFD modelling of multiphase flows

Simon Lo
CD-adapco
Trident House, Basil Hill Road
Didcot, OX11 7HJ, UK
simon.lo@cd-adapco.com

Multiphase models and applications

- VOF
  - Free surface flows
- LMP
  - Droplet flows
  - Liquid film
- DEM
  - Particle flows
- EMP
  - Particle flows
  - Bubbly flows
  - Population balance
  - Boiling heat and mass transfers
  - Interphase mass transfer

NTEC 2014	3 / 31	Volume of Fluid (VOF) model

Volume of Fluid (VOF) model

- Solve equation for volume fraction (based on conservation of mass) to identify location of gas and liquid.

$$\frac{\partial \alpha_i}{\partial t} + \nabla.(\alpha_i u) = \dot{m}_i$$

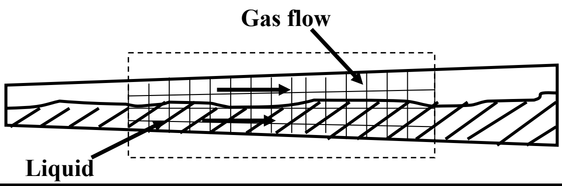
- Momentum equation for the gas-liquid mixture:

$$\frac{\partial}{\partial t}(\rho_m u_i) + \frac{\partial}{\partial x_j}(\rho_m u_j u_i - \tau_{ij}) = -\frac{\partial p}{\partial x_i} + \rho_m g_i + M$$

- Properties of mixture:

$$\rho_m = \sum_{i=1}^{N} (\alpha_i \rho_i)$$

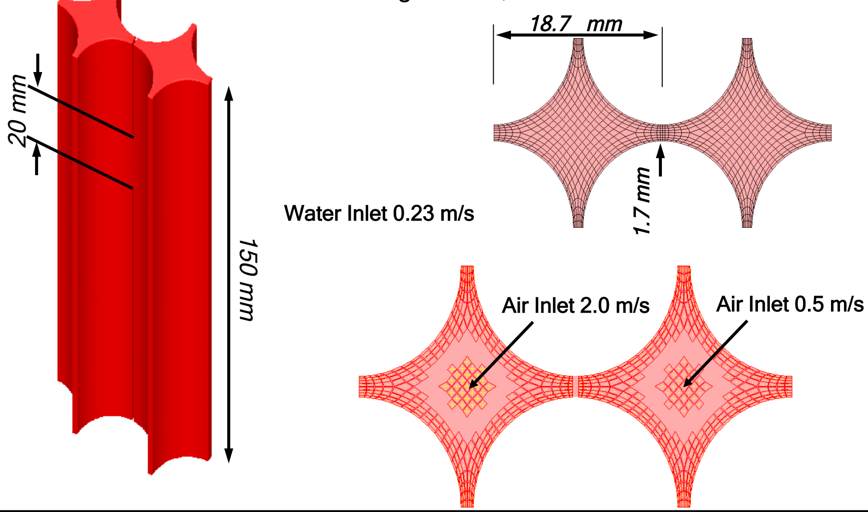
$$\mu_m = \sum_{i=1}^{N} (\alpha_i \mu_i)$$



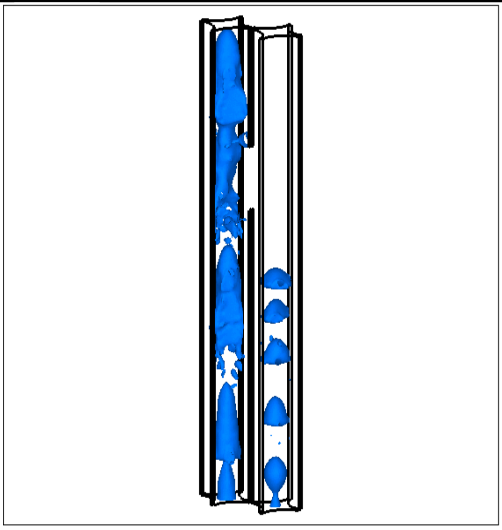
NTEC 2014	4 / 31	Slug flow in interconnected subchannels

Slug flow in interconnected subchannels

Calculation grid 204,512 cells

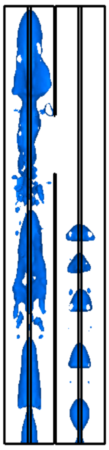


NTEC 2014	5 / 31	Slug flow in interconnected subchannels

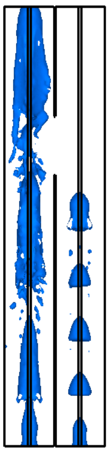


NTEC 2014	6 / 31	Effects of surface tension

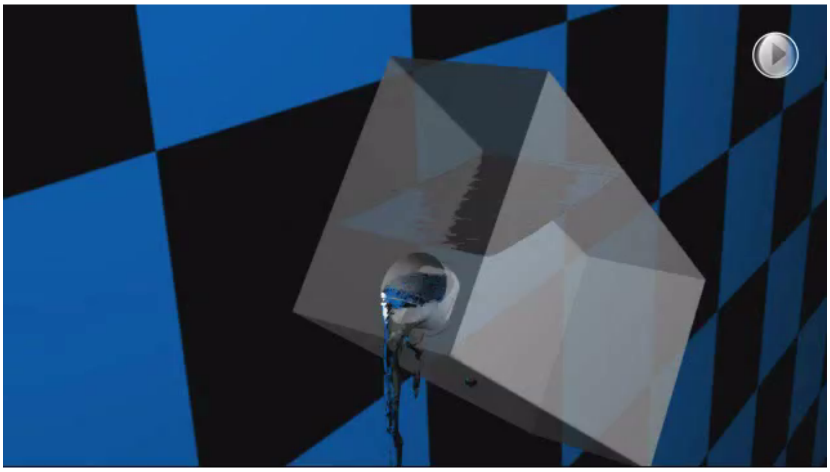
S. Tension = 0.072



S. Tension = 0.06



NTEC 2014	7 / 31	Free surface flow in drink carton

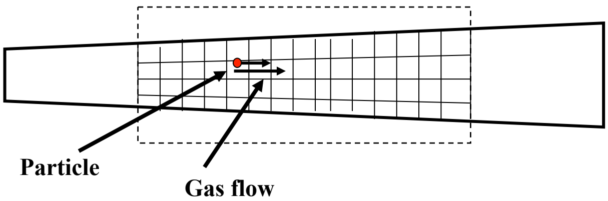


NTEC 2014	8 / 31	Lagrangian model for particle flows

- Equation of motion for individual particle:

$$m_d \frac{du_d}{dt} = F \qquad u_d = \frac{dx_d}{dt}$$

- F = force acting on particle



Spray modelling

- Modified Han et al atomisation model

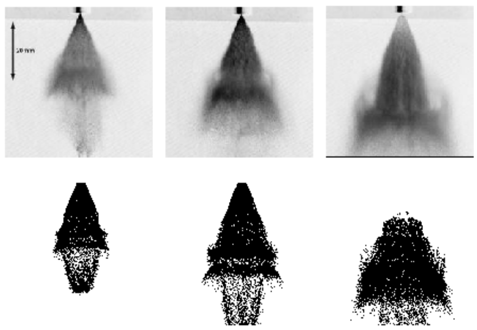
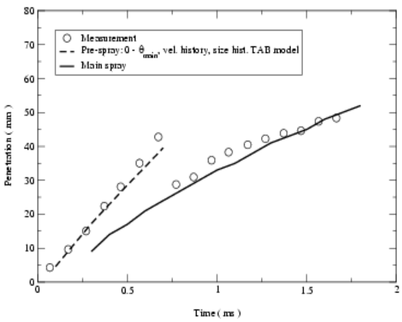
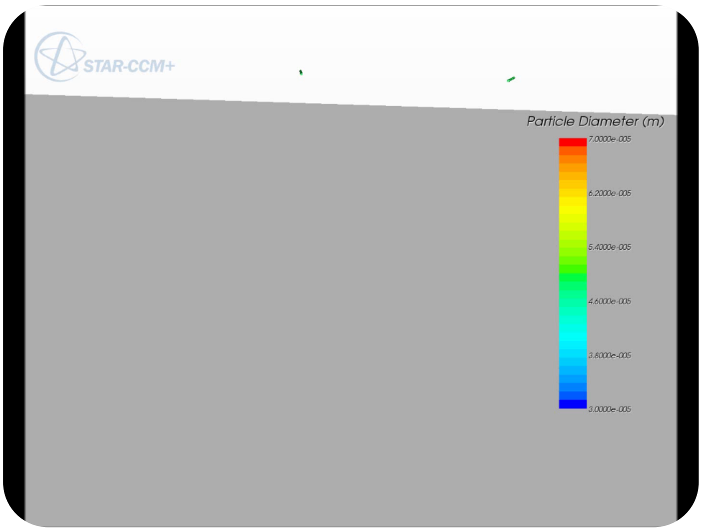


Figure 1: Atm spray images - predictions, at 0.8 ms, 1.2 ms, 1.7 ms, injector Bosch 60°/0° injection pressure 5 MPa, injection duration 1.5 ms

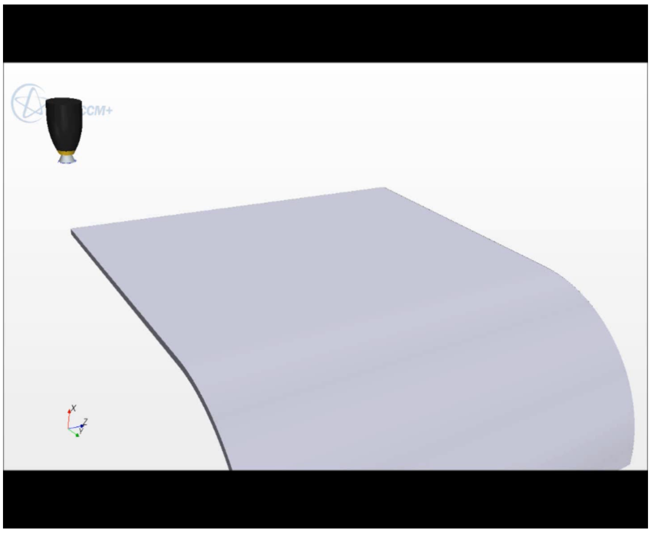


Charalambos (2002)

Droplet collision and coalescence



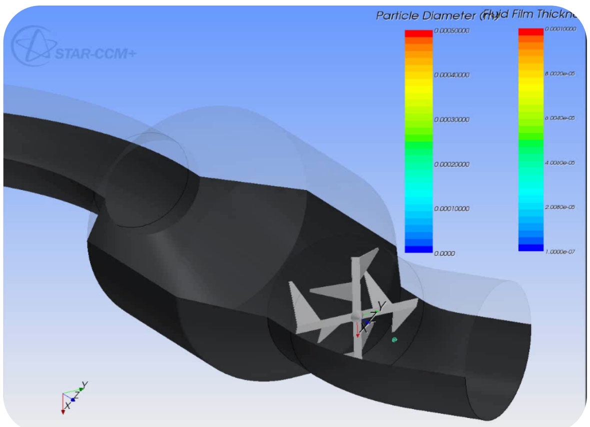
NTEC 2014	11 / 31	Spray coating



NTEC 2014	12 / 31	Fluid film boiling

Simulation of films and their evaporation on high temperature surfaces

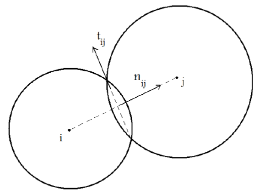
- Walls above saturation temperature of droplet fluid
- Required multi-component film



NTEC 2014	13 / 31	**DEM (Discrete Element Method)**

- Linear momentum of particle:

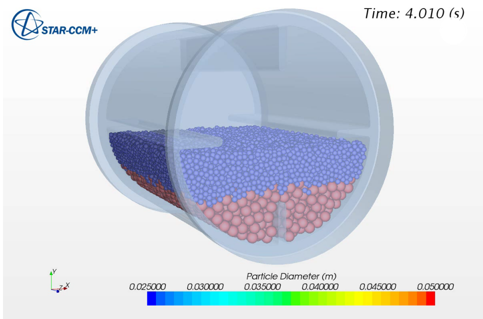
$$m_i \frac{d\vec{v}_i}{dt} = \vec{F}_{Drag} + \vec{F}_{Contact} + \vec{F}_{Other}$$



- Angular momentum:

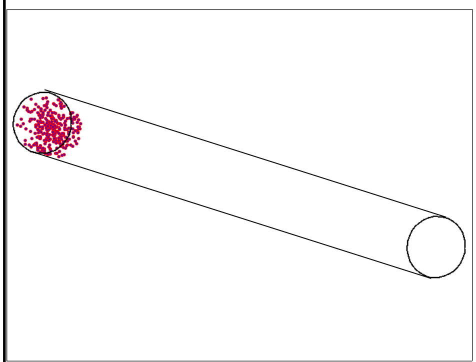
$$I_i \frac{d\vec{\omega}_i}{dt} = \sum_{j=1}^{k} \left[\vec{\tau}_{ij} + \vec{M}_{ij}\right]$$

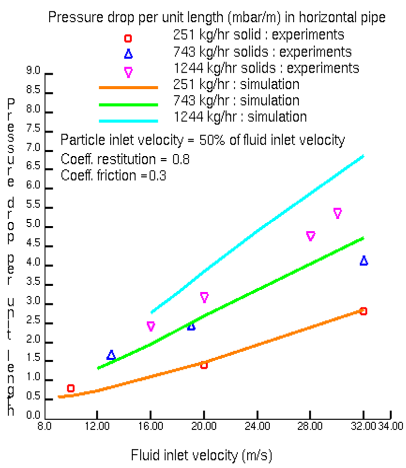
$$\vec{M}_{ij} = -\mu_{roll} \left|\vec{F}_{Contact}\right| \vec{\omega}_i$$



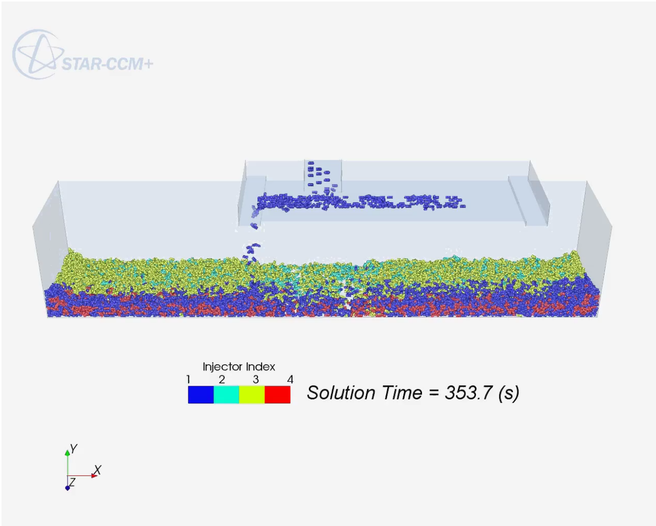
- $\vec{M}_{ij}$ = rolling torque
- μ_{roll} = rolling friction coefficient.

NTEC 2014	14 / 31	**Pneumatic conveying of particles in pipe**





NTEC 2014	15 / 31	Spreading of particles by conveyor belts



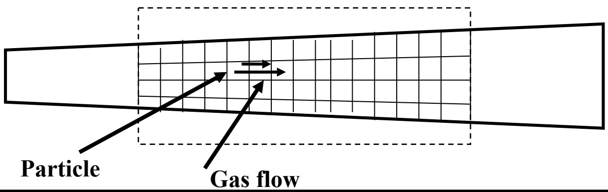
NTEC 2014	16 / 31	Eulerian multiphase model

- Conservation of mass of phase k:

$$\frac{\partial}{\partial t}(\alpha_k \rho_k) + \nabla.(\alpha_k \rho_k u_k) = \sum_{j=1}^{N} (\dot{m}_{jk} - \dot{m}_{kj})$$

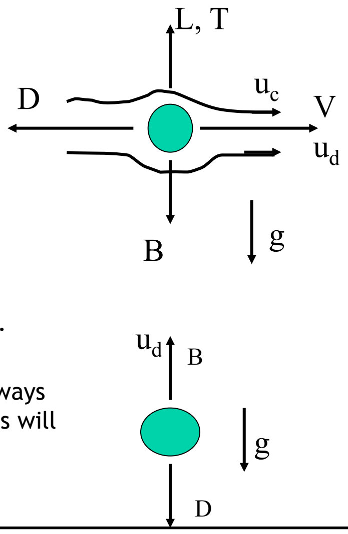
- Conservation of momentum of phase k:

$$\frac{\partial}{\partial t}(\alpha_k \rho_k u_k) + \nabla.(\alpha_k \rho_k u_k u_k)$$
$$= -\alpha_k \nabla p + \alpha_k \rho_k g + \nabla.\alpha_k (\tau_k + \tau_k{}^{t}) + M_k$$

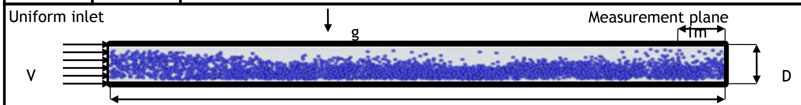


NTEC 2014	17 / 31	**Forces on a particle**

- Forces acting on a particles:
  - Buoyancy, B.
  - Drag, D.
  - Lift, L.
  - Virtual mass, V.
  - Turbulent dispersion, T.
  - Basset force.
  - And others.
- Buoyancy and drag are the dominant ones.
- Basset force is complicated and almost always ignored. Lift, virtual mass and other forces will be considered later.



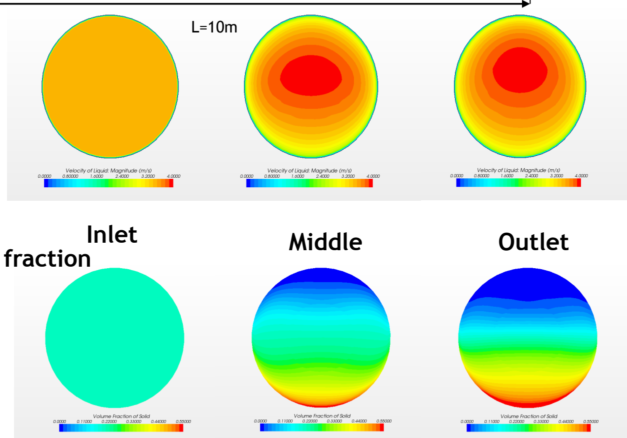
NTEC 2014	18 / 31	**Slurry flow in horizontal pipe**



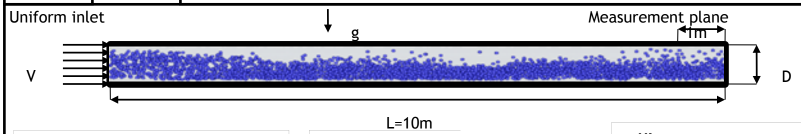
Liquid velocity

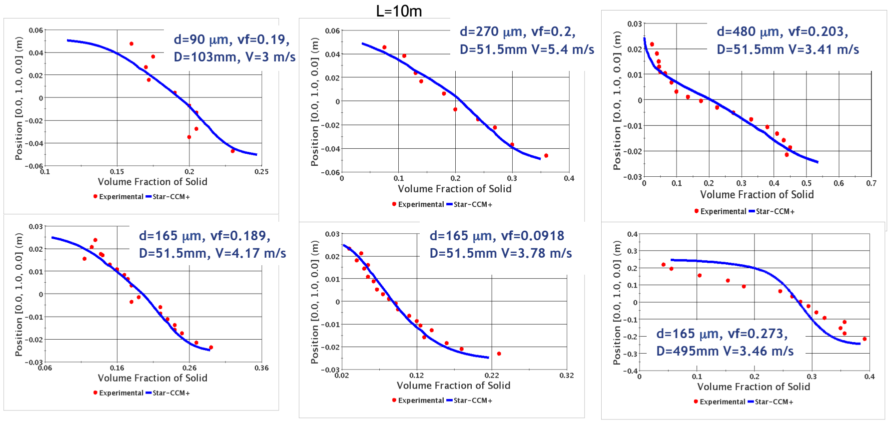
Particle volume fraction

Inlet **Middle** **Outlet**

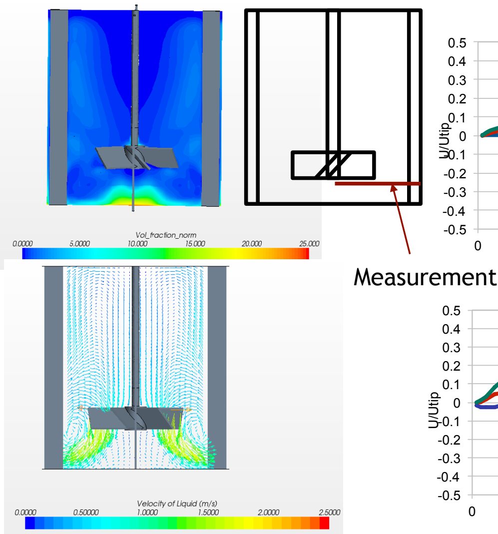


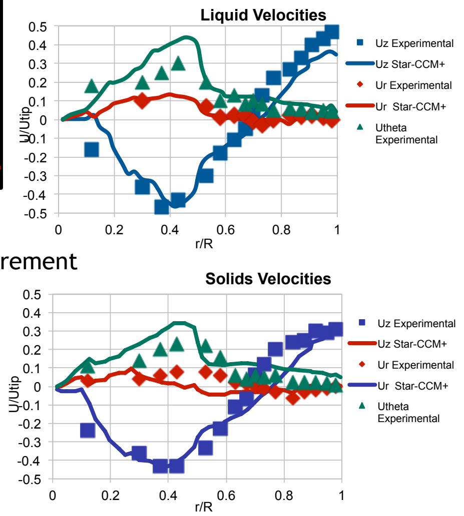
NTEC 2014	19 / 31	Slurry flow horizontal pipe





NTEC 2014	20 / 31	Particle suspension in stirred vessel





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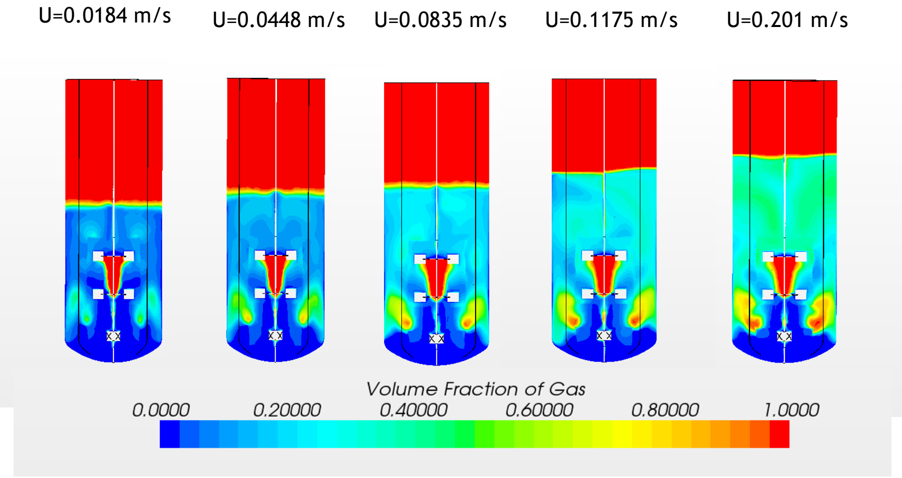
Gas dispersion in stirred vessel

Gas superficial velocity:



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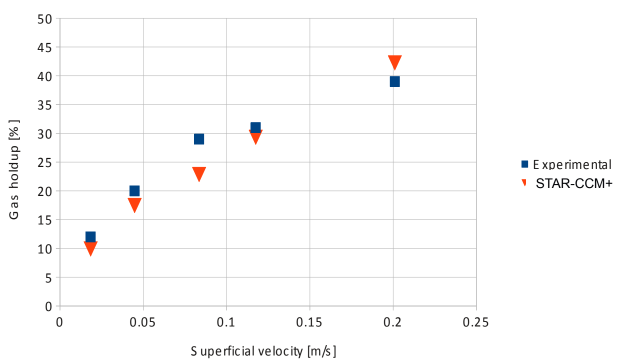
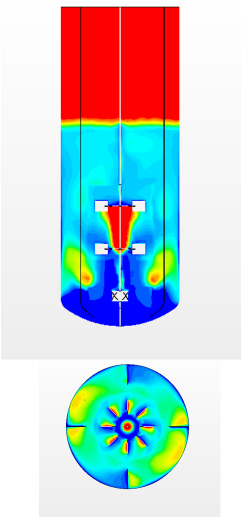
Comparison of gas holdup





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Adaptive MUSIG Model

An Eulerian population balance method for poly-disperse multiphase flows.

$$\frac{\partial \alpha_i \rho_i}{\partial t} + \nabla \cdot (\alpha_i \rho_i \mathbf{u}_i) = \sum_{i \neq j} (m_{ij} - m_{ji}),$$

$$\frac{\partial \alpha_i \rho_i \mathbf{u}_i}{\partial t} + \nabla \cdot (\alpha_i \rho_i \mathbf{u}_i \mathbf{u}_i) = -\alpha_i \nabla P + \sum_{i \neq j} (m_{ij} \mathbf{u}_j - m_{ji} \mathbf{u}_i) + \mathbf{F}_i.$$

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \mathbf{u}_i) = S_i,$$

$$d_i = \sqrt[3]{(6\alpha_i)/(\pi n_i)}.$$

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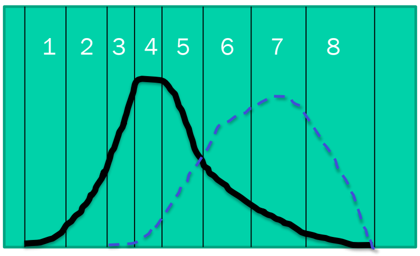
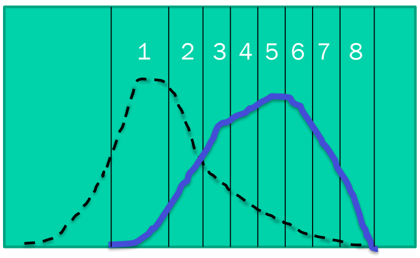
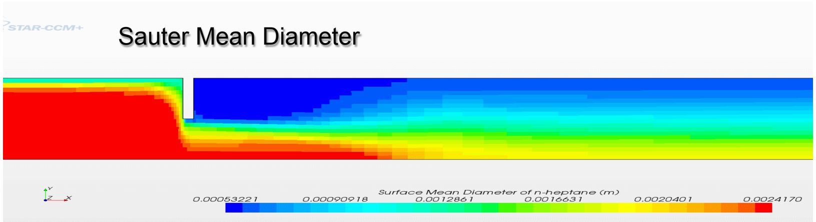
Adaptive MUSIG Model

Mass and number density are redistributed between neighbour groups so that each group has the same mass but new diameters.

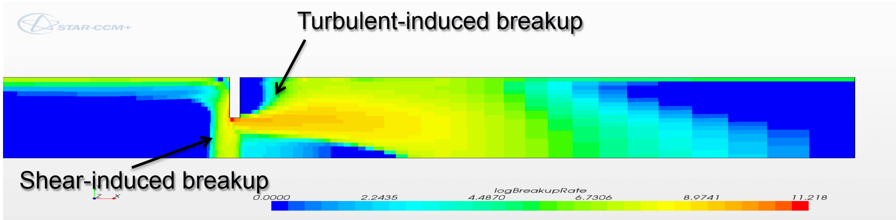




NTEC 2014	25 / 31	Droplet breakup through an orifice



Breakup Rate (log scale)



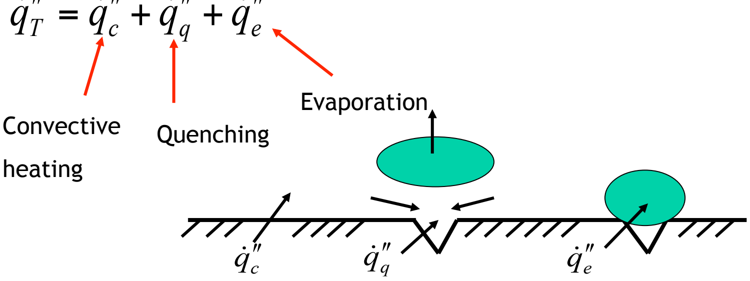
NTEC 2014	26 / 31	Boiling heat and mass transfers

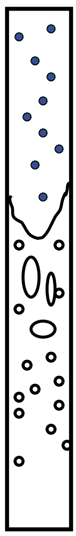
- Conservation of energy for phase k:

$$\frac{\partial}{\partial t}(\alpha_k \rho_k h_k) + \nabla.(\alpha_k \rho_k u_k h_k) - \nabla.\left[\alpha_k\left(\lambda_k \nabla T_k + \frac{\mu_t}{\sigma_h}\nabla h_k\right)\right] = Q_k$$

- Wall heat flux is modelled by three mechanisms:

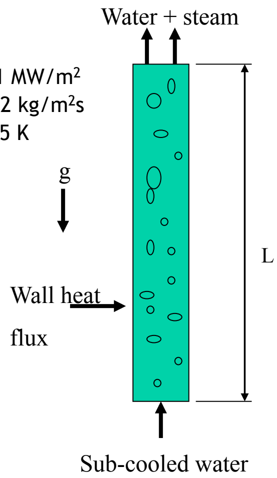
$$\dot{q}''_T = \dot{q}''_c + \dot{q}''_q + \dot{q}''_e$$

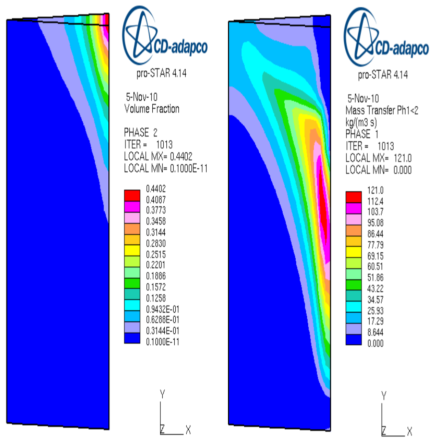




NTEC	27	Bartolomei (1982) - 147 bar experiments
2014	31	

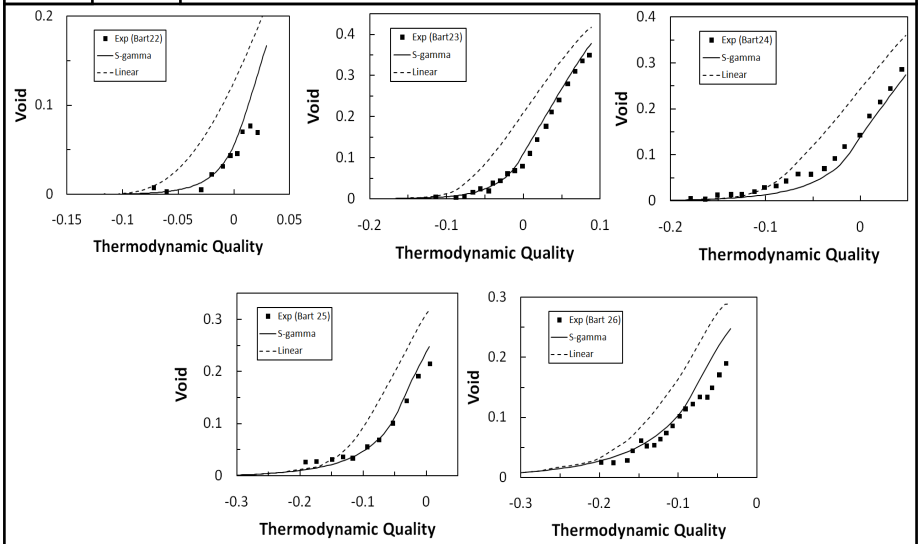
- D = 0.012 m
- L = 2 m
- P = 147 bar
- T_{sat} = 613 K
- Q = 0.42 - 2.21 MW/m^2
- G = 1878 - 2012 kg/m^{2}s
- ΔT_{sub} = 16 - 145 K





Void fraction Condensation rate

NTEC	28	Bart 22-26 : Comparison of axial void profiles
2014	31	



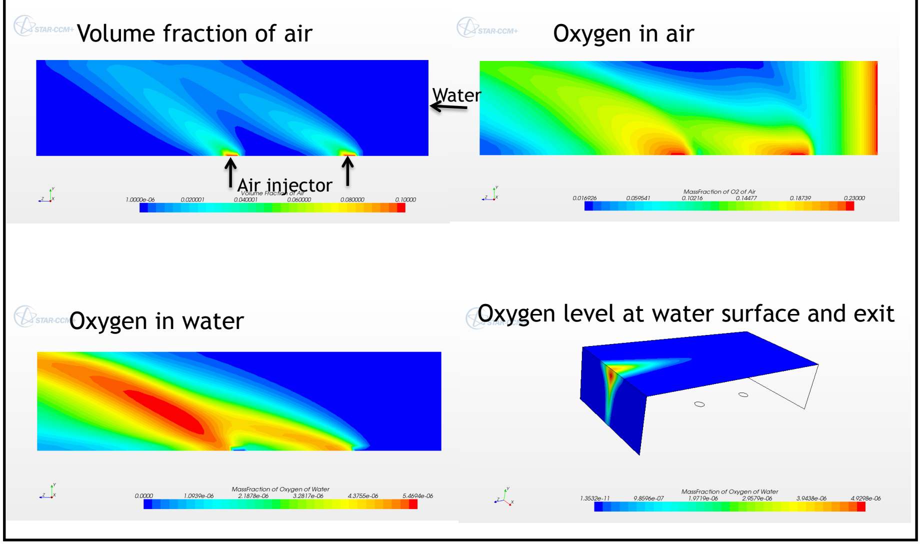
NTEC 2014	29 / 31	Multi-component multiphase model

- General species transport equation for phase k is:

$$\frac{\partial}{\partial t}(\alpha_k \rho_k Y_k)+\nabla.(\alpha_k \rho_k u_k Y_k)-\nabla.\left[\alpha_k\left(D_k+\frac{\mu_t}{\sigma_Y}\right)\nabla Y_k\right]=S_k$$

Y =mass fraction of species or other scalar quantity,
D =diffusion coefficient,
σ =Schmidt number,
S =sources.

NTEC 2014	30 / 31	Oxygen transfer in aeration tank



NTEC 2014	31 / 31	**Summary**

- VOF
  - Free surface flows
- LMP
  - Droplet flows
- DEM
  - Particle flows
- EMP
  - Particle flows
  - Bubbly flows
  - Population balance
  - Boiling heat and mass transfers
  - Interphase mass transfer